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Title: The Optics of Deterrence: How Science Assures the Nuclear Stockpile's Reliability In Lieu of Testing

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The Optics of Deterrence: How Science Assures the Nuclear Stockpile's Reliability in Lieu of Testing
By Chris Johnson[1]

Introduction: Science-Based Stockpile Stewardship in Context

When designing a product intended to perform a certain function and satisfy some set of criteria, the standard engineering method to assess its ability to perform is to test it. This nearly universal concept works consistently, assuring proper function and generally avoiding or mitigating the consequence of failure to within acceptable limits. What would happen if the product developers were told that they must continue to certify and validate the performance *without* testing it, that the landscape in which the product must serve its purpose is constantly evolving, and that the product in question is the United States' nuclear weapons stockpile? This is the position the National Nuclear Security Administration (NNSA) finds itself in; the reliability of the stockpile must be verified without actually testing it to see if it works as intended.

The effectiveness of the United States' deterrence and nonproliferation strategies (and ultimately the safety and security of the entire planet) depends on the stockpile's reliability. The consequences of the product's failure are unacceptable, and the United States must maintain the international posture and preserve optics of complying with the choice not to test. So how is this challenging task addressed, and what is science-based stockpile stewardship? What scientific tools and experiments does the United States use to accomplish this task, including detector development and data acquisition and analysis techniques used to understand results obtained from these experiments? Does what the United States learn from these experiments ultimately bolster confidence in the stockpile and satisfy the needs of U.S. deterrence and nonproliferation objectives? Can the United States depend on science-based stockpile stewardship to certify the stockpile as reliably as full-scale testing?

This research intends to frame some detailed technical aspects of radiation detector design, data acquisition, and analysis for pulsed power experiments used for weapons performance validation in the context of its impact on deterrence and nonproliferation strategy. The specific detector system addressed in this work will serve as an example of how taking a bottom-up approach to understanding the fine details of the functions of individual weapons components and the scientific tools used to validate their performance is both sufficient in lieu of full-scale testing and can be even more robust compared to the top-down approach that was taken in the full-scale testing era.

Historically, since the original 1945 Trinity Test, nuclear weapons would be placed in the stockpile after undergoing several nuclear tests over a period of years. This process accounted for 215 tests above ground and 815 underground, which established a thorough base of legacy data, upon which the Stockpile Stewardship Program (SSP) still relies to inform current weapons

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modeling frameworks. The depth of understanding established by these tests is what ultimately provides conviction to the nuclear laboratories' yearly testimony to Congress regarding the stockpile's ability to perform reliably.[2] In 1992, just after the end of the Cold War, the United States imposed a moratorium on nuclear testing and signed (but has not ratified) the Comprehensive Nuclear Test Ban Treaty (CTBT), which bans weapons tests that generate nuclear yield and prohibits the development of new nuclear weapons. Thus, in 1993, the SSP was born, marking a dramatic shift in weapons design and certification philosophies and techniques. The main driver behind the decision to transition to stockpile stewardship included supporting the Clinton administration's nonproliferation policy, which held the belief that the United States could serve as an example that other nations would follow by not testing.[3]

Not being able to test nuclear weapons obviously raises questions as to whether the stockpile can be successfully certified through science alone. In 2003, approximately 10 years into the SSP, a Los Alamos National Laboratory (LANL) scientist stated that "An underlying concern that has always been an issue with stockpile stewardship is that certifying nuclear weapons without nuclear testing will not address 'unknown' issues that could arise in the nuclear explosion phase of a nuclear weapon's operation," and that they are "waiting on the answer to the question, 'is stockpile stewardship succeeding of failing?'"[4] In the same year, others at LANL more directly declared that "The Laboratory has taken on the challenge to maintain and continue to certify the U.S. stockpile . . . without nuclear testing, however, weapons performance cannot be demonstrated as in the past," seemingly doubting the viability of the SSP.[5] Though the SSP has continuously developed and matured to the present day, the controversy over the SSP has never completely faded away. The Obama administration's stance was that computing and experimental advancements would allow the United States to never need to resume testing, with Obama's undersecretary of state Ellen Tauscher stating in 2011 that, "Our current efforts go a step beyond [nuclear] testing by enabling the labs to anticipate problems in advance and reduce their impact to our arsenal—something that nuclear tests could not do."[6] The controversy still exists, including recently in 2020 when the Trump administration reportedly considered breaking the testing moratorium and during ensuing debate among the administration and Congress as to whether weapons testing on U.S. soil should resume.[7] There was still argument over whether resumption of U.S. testing could induce Russia and China to refrain from conducting weapons experiments that were believed to have generated nuclear yield or help persuade them into three-way arms control agreements.[8]

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[2] Fred N. Mortensen, John M. Scott, and Stirling A. Colgate, "How Archival Test Data Contribute to Certification," *Los Alamos Science*, no. 28 (2003): 38–46, https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-03-5462.
[3] Donald R. McCoy, "Weapon Certification - A Personal View," *Los Alamos Science*, no. 28 (2003): 54–57 (2003), https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-03-4460.
[4] Ibid.
[5] Ibid.; and Mortensen, Scott, and Colgate, "How Archival Test Data."
[6] David E. Hoffman, "Supercomputers Offer Tools for Nuclear Testing – and Solving Nuclear Mysteries," *Washington Post*, November 1, 2011, https://www.washingtonpost.com/national/national-security/supercomputers-offer-tools-for-nuclear-testing--and-solving-nuclear-mysteries/2011/10/03/gIQAjnngdM_story.html.
[7] Ferenc Dalnoki-Veress and Miles A. Pomper, "A restart of nuclear testing offers little scientific value to the US and would benefit other countries," The Conversation, updated August 3, 2020, https://theconversation.com/a-restart-of-nuclear-testing-offers-little-scientific-value-to-the-us-and-would-benefit-other-countries-141168.
[8] William Courtney and Frank G. Klotz, "Nuclear Testing not Needed Now," RAND Blog, June 11, 2020, https://www.rand.org/blog/2020/06/nuclear-testing-not-needed-now.html.

It could easily be argued that there is simply no better way to certify weapons performance than through full-scale nuclear testing; as pointedly marked by an anonymous Livermore designer in 2011, "To say that [the SSP] is better than underground testing is silly. . . . If you want to know if something works, you have to test it."[9] It just makes sense—the best way to be sure that something works is to try it out and see if it works; the concern that it may not be possible to achieve confidence without testing is understandable. The issue with this thinking is that it overlooks the fact that testing-based certification permitted a top-down approach to be taken toward weapons design philosophy. Essentially, before the testing moratorium, it was not as important to *understand how* the devices worked, so long as there were assurances that they did, in fact, work. Although it poses significant challenges, the testing moratorium forces a bottom-up approach to be taken toward the design and certification process, where the details of the physics and material properties of each system component must be thoroughly understood in order to confidently verify the performance of the system. It could be said that while nuclear testing was a convenient tool, it was also the world's biggest shortcut.[10]

Although it comes at the expense of substantial effort and financial investment, using science to steward the stockpile has forced designers to ask and answer vital questions that would otherwise not have been considered if nuclear testing were permitted. Understanding these details can ultimately provide *more* confidence in the stockpile than simply knowing whether or not a given design works. The thesis of this work is to back the effectiveness of the bottom-up approach by exploring the design, calibration, capabilities, limitations, and future work to be done to improve a specific detector system used to diagnose pulsed accelerator beams at facilities used for weapons certification experiments. The particular system addressed herein is one small piece of a vast field of study and by no means exhaustively accounts for the effectiveness of the SSP on its own. It does, however, demonstrate the level of detail and rigor that must be considered in all aspects of science-based stewardship in order to result in an effective and robust program.

Background: The Premier Stewardship Tools and How They Are Used

In order to gauge effectiveness and get a sense of the state of stockpile stewardship, it is necessary to understand some of the fundamentals of how nuclear weapons function and how they are observed and verified, including current capabilities, their limitations, and objectives for future capabilities and techniques that are under development. Though not exhaustive, the description given in this work touches upon some of the key elements of stockpile stewardship. Evaluating the effectiveness of the detector system described in this work requires understanding the background of the weapon components whose performance is examined by the experiments.

The pit, or primary, is one of the most important components of a two-stage thermonuclear weapon, and validating its performance is of high priority to the SSP. The pit is a plutonium component that, upon ignition of the device, is driven to implode by the high-explosive (HE) that surrounds it in such a way that it is compressed to a supercritical

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[9] Ibid.; and Hoffman, "Supercomputers Offer Tools."

[10] J.C. Mortz, "Without Testing: Stockpile Stewardship in the Second Nuclear Age," Stanford University, 2014.

configuration on a very fast timescale. A supercritical system is defined as one whose reactivity is greater than one (the ratio of free neutrons entering the system due to fission exceeds the number exiting the system). The primary's ability to achieve this state with the correct timing is paramount to the overall performance of the device. Therefore, understanding its reactivity as a function of time is a major focus of weapons research and development under the SSP. Some major questions that science-based stockpile stewardship intends to address regarding the pit include verifying the performance of aging components that could be affected by degradation beyond the components' design life and the performance of components that are being made at new facilities with different processes, such as new LANL pits compared to legacy Rocky Flats units produced before the facility was shut down in 1989.

On a basic level, the bottom-up approach to certification involves piecing together the fundamental physics relevant to the behavior of each weapon component and material and using that information in a computational calculation of how the whole system works. Once a completed model is established, it is then used to predict the results of past nuclear tests and validated against legacy data. Under the SSP, in order to further verify and establish confidence in the model, predictions are also compared to results of nonnuclear tests known as integral experiments, where the function of some component of the system is carried out and observed without generating nuclear yield.[11] The SSP relies on data obtained from these integral experiments that observe the behavior of subsystems under weapons-relevant conditions without stepping into the territory of a nuclear test.[12]

The Dual-Axis Radiographic Hydrodynamic Test Facility (DARHT) at LANL is a pulsed power linear accelerator consisting of two perpendicular radiographic X-ray beams of ~20 MeV endpoint energy where integral experiments known as hydrodynamic tests (or hydrotests) are carried out. In a hydrotest, a primary that uses a dense metal surrogate material intended to represent the behavior of plutonium (instead of actual plutonium; policy restrictions prohibit HE-driven plutonium experiments to take place at DARHT) is driven to compress by an HE detonation as would occur in a weapon. The term "hydro" is used because, under the intense heat and pressure generated by the HE detonation, the heavy metal begins to flow like a liquid.[13] The purpose of the DARHT accelerator is to take X-ray images of the implosion process, allowing the internals of the object to be visually observed under dynamic conditions. DARHT's first axis is a single-pulse machine, which, combined with images from the perpendicular second axis, provides the capability to reconstruct a three-dimensional image. The second axis is a four-pulse machine; by delivering four short X-ray bursts in rapid succession, a short "movie" of the implosion may be obtained. Analyzing properties of these X-ray images allows the reactivity of the primary as a function of time to be inferred, ultimately indicating whether the device will perform as expected. Hydrodynamic tests are the cornerstone of primary design because they provide evidence that the assembly of the primary materials of a real weapon into a supercritical configuration proceeds as planned.[14]

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[11] Ibid.; and McCoy, "Weapon Certification."
[12] R.J. Juzaitis, "Science-Stockpile Stewardship: An Overview," *Los Alamos Science*, no. 28 (2003): 32–37, https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-03-5302.
[13] Chris Rose, "DARHT: An Overview," IEEE Colorado Springs Chapter, 2006, https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-13-27536.
[14] Ibid.; and Mortensen, "How Archival Test Data."

While dynamic radiography of imploding surrogates conducted at DARHT is currently the highest-fidelity experiment that can be carried out for observing primary performance in the absence of nuclear testing, there is still a need to expand capabilities to observe true weapons plutonium under dynamic conditions.[15] Put another way, "Certifying the implosion dynamics of a nuclear device without nuclear testing requires precise data on the behavior of plutonium."[16] In order to accomplish this, a program known as Enhanced Capabilities for Subcritical Experiments (ECSE) is currently underway. The main diagnostic capability for ECSE will be a new pulsed power accelerator known as Scorpius, which will be very similar to DARHT but installed below ground at the Nevada National Security Site (NNSS), where underground tests used to be conducted during the nuclear testing era. In this location, dynamic experiments involving radiography on plutonium pits driven by HE will be permitted to take place. These are called subcritical experiments because the plutonium is dudded such that it remains subcritical and does not generate nuclear yield when dynamically compressed. This subcritical experiment capability will transform stockpile stewardship methodology by allowing observers to come as close as possible to observing true nuclear weapon behavior without entering the realm of a nuclear test.[17] These subcritical tests will enhance the United States' ability to obtain accurate data on the plutonium primary's reactivity as a function of time.

An additional experimental tool intended to further constrain primary reactivity and provide a confirmatory measurement to radiography on subcritical experiments known as Neutron Diagnosed Subcritical Experiments (NDSE) is currently under development. NDSE aims to induce fission in the object by bombarding it with a short burst of neutrons and measuring prompt gamma rays that result from the fission, such that the reactivity may be inferred.[18] In order to make this measurement accurately, it is essential to understand all neutron sources that could contribute to reactivity in the object, particularly including neutron backgrounds in the accelerator beam itself.

Detector Design: What Do Detectors Have to Do With Deterrence?

These experimental tools, while not the only things that make the SSP work, make it possible to obtain knowledge that is on the forefront of what can possibly be understood about weapon performance (under a full-scale testing regime or otherwise). In order to maximize the utility of the aforementioned tools and understand the data obtained from experiments conducted with them, the designs of their beamlines must be optimized and observers must be able to understand their beams' contents. It is not as simple as just detonating an object in an accelerator beam and having the machine spit out an answer. It is necessary to field advanced radiation detection systems on these experiments, both in the accelerator beamlines and in the object of interest's scattering field, in order to obtain data that helps infer what is going on. As is the case in any beam-on-target experiment where products of the beam-target interaction are detected in order to infer information about the target, the results are only as good as one's understanding of

[15] Mary Hockaday, "DARHT Overview," *Albuquerque Journal*, 2006.
[16] E.M. Hanson, "Stockpile Stewardship Past, Present and Future," New Mexico Network Women in Science and Engineering 25th Meeting and Symposium, 1999.
[17] D. Del Mauro, "Scorpius is Posed to Make a Sting in Stockpile Stewardship," *LANL Today*, 2018.
[18] J.P. Lestone et al., "What is it: NDSE?," What is it Seminar Series, 2019.

the beam contents, including any unwanted sources of background. In the case of NDSE, where fission products are measured and used to infer reactivity of the object, it is imperative to understand any neutron backgrounds in the accelerator beam that could contribute to increased reactivity in the object that would not occur in the absence of the beam. Understanding these backgrounds and implementing a detector system that is capable of doing so will help enhance the robustness of the SSP by improving the quality of the information obtained from NDSE.

X-rays in the accelerator beam are energetic enough that they can produce substantial neutron backgrounds through a process called photodisintegration by scraping against materials in the beamline and ejecting scattered neutrons from nuclei in the material. While the X-ray energies needed to radiograph the dense metals of the object are too high to completely eliminate neutron contamination from the beam, the beamline may be designed such that it minimizes neutron production, and the backgrounds may be corrected for in reactivity calculations if they are well understood. The development of detector system intended to be placed directly in the beam is underway so that the energy spectrum, intensity, and timing of neutron backgrounds in the DARHT and Scorpius beamlines may be characterized (as all of these properties contribute to reactivity in the object that would not occur in the absence of the beam). The design, calibration, capabilities, and limitations of this detector system will be used as a representative example of the fine details of the scientific process that allow the bottom-up approach to be taken to weapon design and certification under the SSP.

The detector design process begins by considering design constraints: What do the detectors need to measure? What are the design limitations? And which priorities need to be optimized for (oftentimes, multiple constraints can be at odds with each other, requiring careful consideration in a trade space between desired attributes)? The dominant constraints for this in-beam detector system include:

1. The system must be capable of measuring direct beam X-rays and neutron backgrounds in such a way that they may be separated.
2. The system must generate and collect a substantial enough signal such that it may be calibrated for its energy response.
3. In order to suitably resolve the beam and background signals in time relevant to the timescale of the object, the system must have exceptionally fast timing response.
4. The detector system must place only a minimal amount of material in the beamline in order to minimize beam scatter and interference with other experimental diagnostics.

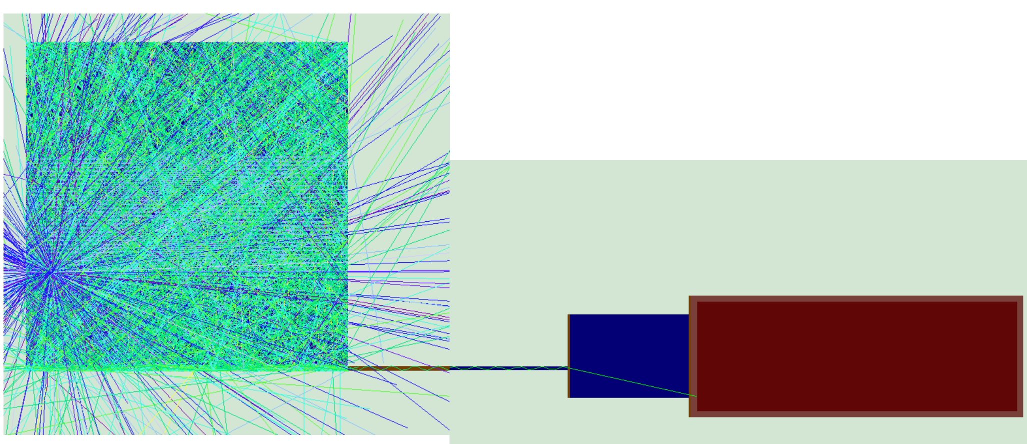
The accelerators generate high radiation and radiofrequency (RF) environments that impose uniquely challenging constraints on the detector system, including:

5. In order to prevent signal contamination due to RF interference in the electrical components of the system, electrical components must be placed remotely from the beamline.
6. In order to prevent excessive signal contamination due to radiation interactions in optical light-coupling components of the signal collection system, these components must also be placed as far away from the accelerator beam as possible.

A brief review of the basics of detector function and data acquisition techniques will be helpful for understanding how to establish and satisfy these constraints. Gamma rays (this term can be used interchangeably with X-rays here) and neutrons can be difficult to measure because they cannot be seen, felt, or heard and do not carry charge. Therefore, detection of gammas and neutrons for this application relies on selecting detector materials with which the particles interact in such a way that generates visible light (or optical photons). This visible light must be collected and converted into electric charge, which is the electronic signal that is ultimately collected and stored for analysis.

In this case, the detector materials chosen for the in-beam monitors are fused silica Cherenkov radiators and plastic scintillators (specifically BC-408 scintillator material). Light generated in the detector materials by beam interactions is transported to a remotely-housed photomultiplier tube (PMT) (as required by constraints 5 and 6, this component cannot be directly connected to the detector material in the beam) by a light collection system that uses a wavelength shifter (WLS) and an optical fiber. The WLS is a special optical component intended to absorb and reemit light, changing both its wavelength and phase space in such a way that it increases the system's light collection efficiency by making photons more likely to travel to the optical fiber than if the WLS were not present. Photons that enter the optical fiber are then piped to the PMT, where they impinge the PMT's photocathode and eject photoelectrons. Photoelectric ejection occurs with a quantum efficiency of around 20 percent, depending on the wavelength of the incident light. The ejected photoelectrons ultimately cause an avalanche of many more electrons as they cascade along the PMT's dynode chain through its high voltage field, which becomes the electronic current that is collected and stored by the data acquisition electronics. Figure 1 shows a simulated image that represents light generated in a gamma interaction in the detector propagating through the light coupling system and to the PMT. In this particular event, only a single photon out of the thousands generated in the interaction reaches the PMT at the end of the fiber, visually representing the fact that this detector has very low light collection efficiency. The fiber is artificially trimmed in the image for visual clarity; it would be much longer if drawn to scale.

Figure 1: Light Collection in a Simulated Gamma Event



A simulated image of an interaction in the detector where a single photon out of many generated in the interaction reaches the PMT.

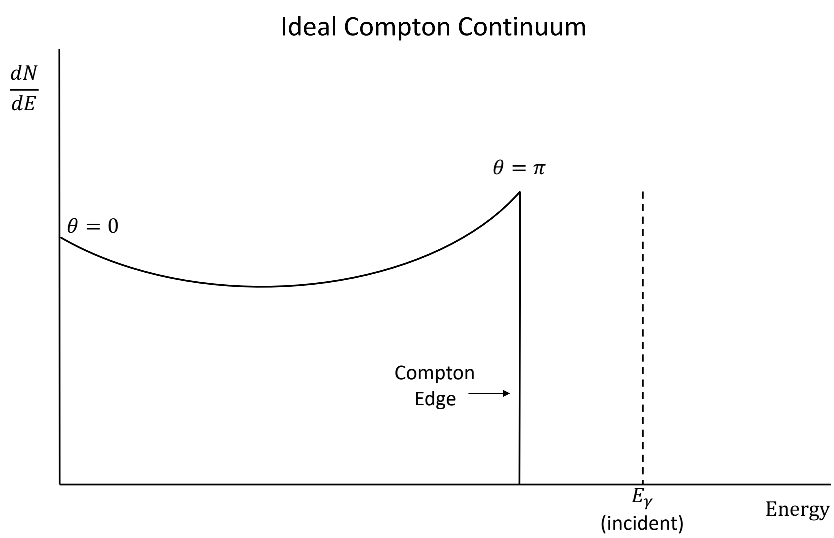
From start to finish, for a single particle that deposits some amount of energy to the detector material, the amount of light generated will be proportional to the energy deposit, some amount of these photons will be collected and hit the PMT, some of these will eject photoelectrons according to the PMT's quantum efficiency, the signal will be amplified by the PMT's gain, and a current pulse will be collected. Therefore, if the response of each detector component is known (i.e., the detector is characterized), then the size of the pulse collected will be correlated to the amount of energy deposited by the particle in the original interaction with the material.

The interaction mechanism for gamma rays in each detector material is Compton scattering, where a gamma ray deposits some of its energy to an electron in the detector material, causing the electron to recoil through the material. In the plastic scintillator, the scintillation happens when the recoil electron excites and ionizes molecules along its track, which then emits visible light upon relaxation. In fused silica, the scattered electron can be moving faster than the phase velocity of light in the material, which causes visible light to be generated through Cherenkov emission. In the plastic scintillator, the neutron mechanism is proton recoil, where an incident neutron collides with a proton (or hydrogen nucleus) of the detector material. The scattered proton then excites detector material along its track, which emits visible light upon de-excitation. While light can be generated in the plastic by both neutron and gamma interactions, there is no mechanism by which neutrons in the energy regime relevant to these accelerators can excite a scattered silicon or oxygen nucleus in the fused silica to above the phase velocity of light in the material. Plastic scintillator and fused silica are excellent materials to satisfy the constraint that the detector system must be able to distinguish gamma and neutron signals in the beam. This is a bit of a simplification, but if (and this can be a big "if") both detectors' response functions are known, then the gamma content of the beam can be determined from the fused silica signal, and the neutron signal can be extracted by subtracting the gamma-only signal from the combined gamma plus neutron signal of the plastic, leaving only a neutron signal behind. If one has a separated neutron and gamma signal in a series of multiple pairs of detectors along the beamline, then the neutron flux, spectrum, and timing can be deconvolved through an extended time-of-flight method. The fundamental idea behind time-of-flight is that if one knows when something was at point A and point B, and one knows how far apart the points were, then one knows how fast the object was moving (and therefore how much energy it had). The case of the accelerator beam is more complicated because instead of a single particle, there are many different particles (of two different species) with various energies, which are all arriving according to some time distribution. With careful planning of an appropriate number of detectors and spacing between them, mathematical analysis can be done on the data collected to constrain these properties of the neutron background in the beam.

In practice, establishing the detectors' response functions, however, is not always straightforward. The need for the detector to be connected to the PMT through an optical fiber mandates that the detector has very low light collection efficiency *and* that the uniformity of the light collection efficiency throughout the bulk of the detector be low. Essentially, it is really difficult to pick little bits of light off of the detector with a tiny optical fiber and still maintain a correlation between the size of the pulse that is collected and the energy deposited in the detector. For example, a particle that deposits a lot of energy and generates a lot of light in a location in the detector where the light collection efficiency is relatively very low may result in just a few or even zero photons reaching the PMT and generating signal. Conversely, a gamma ray of the same energy that deposits only a small amount of its energy will generate only a small amount of light. If this collision happens in a location in the detector where the light collection efficiency is relatively high, a substantial signal could be collected. Comparing these cases, it becomes obvious that, with low enough light collection efficiency and uniformity, the detector cannot discriminate between high and low energy deposits, rendering it essentially incapable of resolving energy at all!

In the case considered here, nearly all of the light that is generated in the detectors gets wasted, with only a single or a few optical photons making it to the PMT in an event. This low light collection efficiency is perfectly acceptable in the environment where the detectors are designed to be fielded. The accelerator beams are very intense, so they produce a lot of light in the detectors and collecting just a small fraction of the light still results in a substantial signal. The low light collection efficiency and uniformity, however, present major challenges in a calibration scenario where a lower-intensity radiation source of known energy is being used to determine the detector's response (which is necessary to achieve in order to extract useful information from the signal obtained by the detector when fielded on an accelerator experiment). When a plastic scintillator or Cherenkov radiator has high light collection efficiency and uniformity (as they would be designed for most applications), the calibration process is fairly straightforward. Collecting many pulses from many gamma interactions and plotting the sizes of the pulses results in a probability distribution of pulse sizes that corresponds to the probability distribution of energies that the gamma rays could deposit to the detector material. This is known as a Compton continuum and has a distinct feature in the distribution known as the Compton edge, which represents the maximum energy that can be deposited to an electron in the detector material by a gamma ray of a given energy. Figure 2 shows an ideal Compton continuum that represents the probability distribution for a gamma ray of energy E_γ to deposit some amount of energy in a scattering event with scattering angle θ.

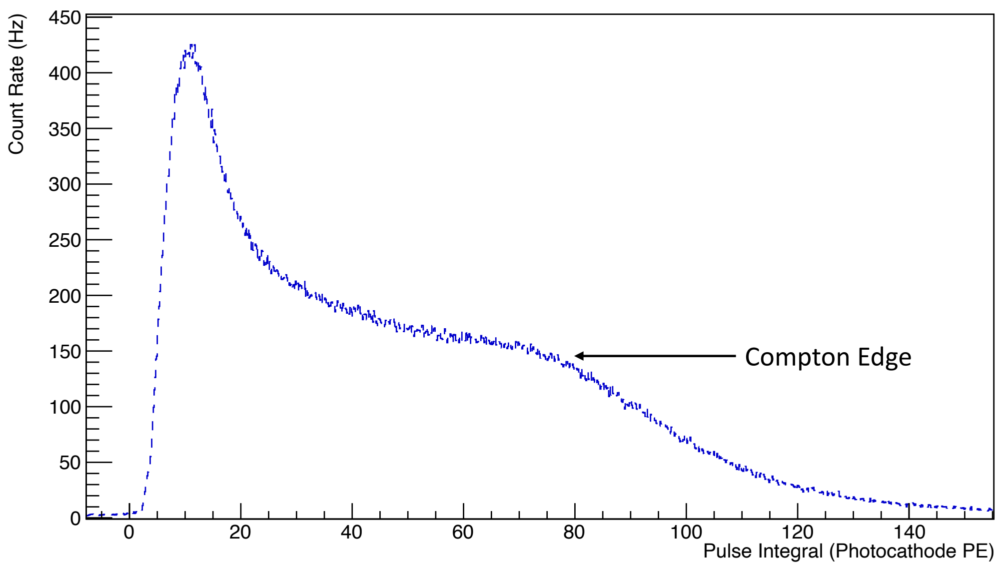
Figure 2: Features of a Compton Continuum



The Compton distribution of energies that a gamma of energy E_γ may deposit to an electron in a scattering event.

If the Compton edge feature presents in the distribution of pulse sizes collected by the detector system, then a certain pulse size is correlated to a known energy deposit, and the light transport efficiency of the detector is considered to be calibrated (given, of course, that the detector's light output and the PMT response are well known, which is usually the case). This calibration must be achieved in order for the detector system to be usefully fielded on weapons performance experiments. Figure 3 represents a pulse size distribution collected by a real detector when bombarded by ^{60}Co gamma rays with adequate light collection efficiency and uniformity. The Compton edge feature is much less sharp compared to the ideal distribution in Figure 2 due to light collection and PMT effects but may still be resolved for calibration purposes.

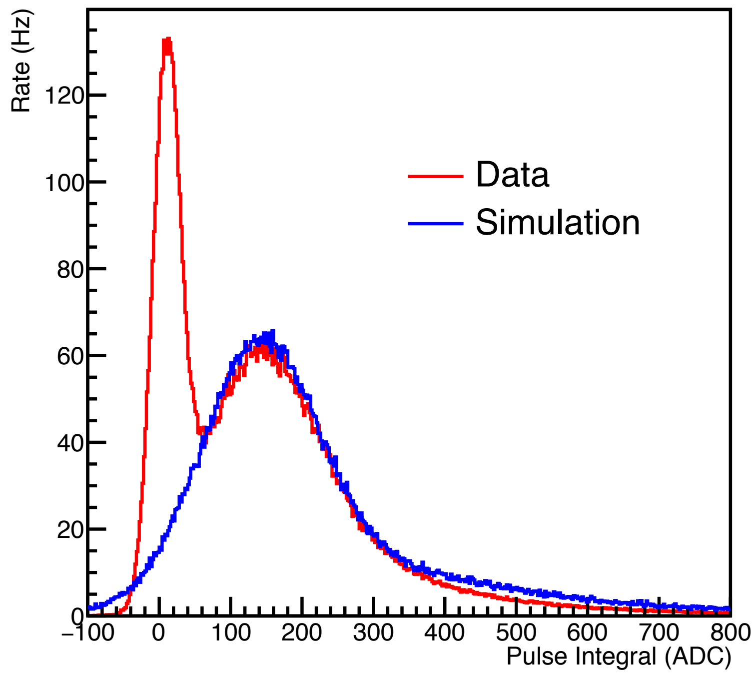
Figure 3: A Compton Continuum Obtained in a Calibration Experiment



With a real detector with adequate light collection efficiency and uniformity, the Compton edge will present in a pulse size distribution, thereby allowing a pulse size to correlate to a known amount of energy deposited in the detector. Pulse size is given in units of photoelectrons ejected by the PMT photocathode here.

If, however, one has taken a series of runs with a calibration source and the Compton edge does not appear in the pulse size distribution, how does one proceed? How does one calibrate a detector's light collection efficiency when it has no energy resolution at all? The pulse size distribution may look something like the red trace in Figure 4, which was acquired with a ^{60}Co source incident on an in-beam monitor. The detector's response *must* be understood if it is to be usefully fielded on weapons experiments, but this presents a major challenge in the detector characterization process.

Figure 4: Comparing Experimental Data to Simulated Results



When light collection efficiency and uniformity are low, as in the case of the in-beam monitors, the Compton edge does not present in the pulse size spectrum. The large feature around 0 ADC is due to digitizer trigger threshold and baseline effects and is not part of a Compton distribution. Pulse sizes are given in units of ADC here, which represents digitizer conversions from analog PMT current to digital signal. A simulated distribution is also plotted in blue, which will also be discussed.

There must be some way to relate the pulse size distribution to the number of photons that end up generating signal out of the number that is produced in the detector material. The key to accomplishing this is modeling and simulation. Geant4 is the simulation framework used for these types of calculations because it can track radiation and optical particles from birth to death.[19] Once an application representing the detector system is built in the simulation, high-performance computing can be used to run many gamma rays incident on the detector. Some of the gamma rays will interact with the detector and generate optical photons, some of which will reach the WLS, be absorbed and reemitted, reach the optical fiber, and be piped to the PMT. The simulation stores information for each event, including where the gamma interacted in the detector, how many optical photons were generated, what their wavelengths were, and how many ended up reaching the PMT. If the PMT is well calibrated, the simulation results can be post-processed by applying the PMT response to each simulated event to convert the number of photons to a pulse size. This process ultimately establishes a simulated pulse size distribution that, in theory, will match the experimentally obtained distribution if the simulation was executed correctly. The simulated distribution for the in-beam monitor is shown in blue in Figure 4 and matches the experimental distribution well (for pulse sizes above where digitizer effects dominate).

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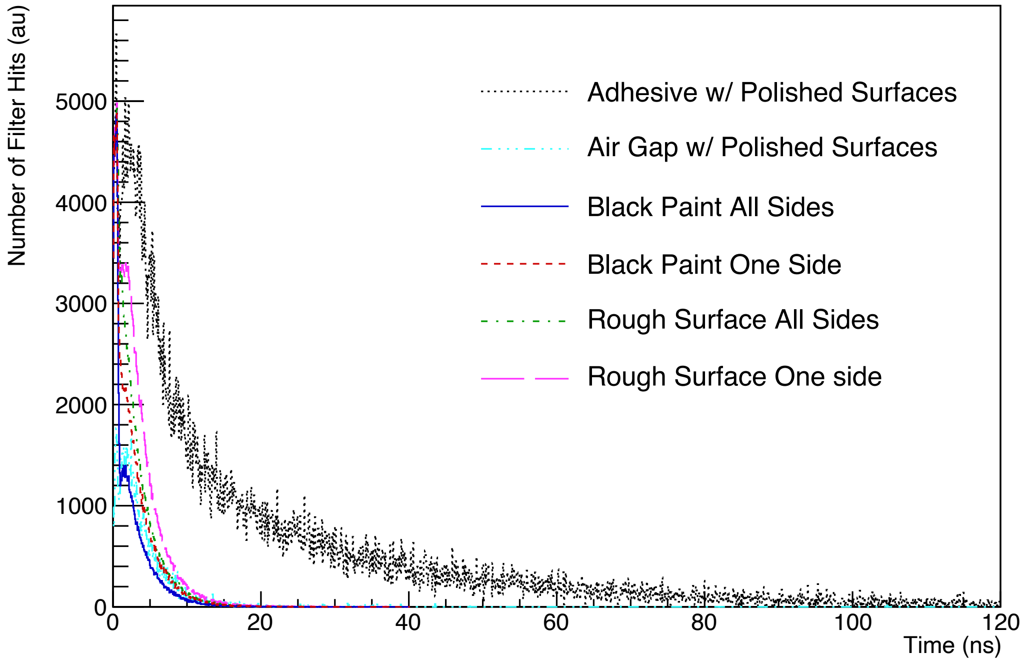
[19] S. Agostinelli et al., "Geant4: A Simulation Toolkit," *Nuclear Instruments and Methods in Physics Research Section A* 506 (2003): 250–303, doi:10.1016/S0168-9002(03)01368-8.

Once the light collection efficiency and uniformity of the detector are sorted out, modeling and simulation can also be used to characterize the detector's timing response. Not all photons take the same amount of time to reach the PMT after they are generated in the detector. It is extremely important to both minimize the arrival time spread *and* understand the time spread thoroughly (i.e., detectors with fast time resolution are desirable so that they can be used for time-of-flight calculations on timescales relevant to the accelerator beam). This is absolutely essential for using time-of-flight to analyze data acquired by the in-beam monitors on pulsed power experiments.

The in-beam monitor system has been through a few design iterations and is constantly under development in order to more accurately characterize its energy and timing response. Design tweaks to increase the timing resolution include changing the WLS material, potentially having custom WLS material with extra fast time response made, and using various surface treatments on the detectors themselves. At the expense of light collection efficiency, the timing response can be improved by roughing or painting some edges of the detector. This causes optical photons to reflect out of the system, be absorbed, or otherwise effectively "die" instead of being reflected back into the system at the treated edge. This obviously results in less of the optical photons reaching the PMT, but it prohibits photons from taking roundabout oblong paths to the PMT, ultimately reducing the arrival time spread by only keeping photons that take faster, more direct, paths to the PMT. Figure 5 represents simulated arrival times at the detector end of the fiber for the fused silica in-beam with various couplings to the WLS bar and various detector surface treatments.

Figure 5: Simulated Arrival Time Distributions for Various Surface Treatments



Simulated photon arrival time distributions at the detector end of the fiber for the fused silica in-beam detector demonstrate the effects of various detector-to-WLS coupling methods and detector surface treatments. Adhesively coupling the detector to the WLS and using all polished detector surfaces has the greatest arrival time spread and best light collection efficiency, while using an air gap to couple the detector to the WLS and using black or rough surface treatments to eliminate reflections in the detector improves the time resolution at the expense of light collection efficiency.

A delicate balance needs to be struck in this trade space between light collection efficiency and timing response. Additionally, once the design is finalized, the simulated timing response will need to be validated experimentally. Some proposals for this timing experiment are under consideration but are challenging and generally beyond the scope of this work. Once these tasks are accomplished and the detector system is finalized, it will be fielded on hydrodynamic tests at DARHT and subcritical experiments at Scorpius. Understanding neutron backgrounds in the beam will ultimately bolster the fidelity of NDSE measurements, allowing observers to further constrain primary reactivity on subcritical experiments, which will enhance the robustness of the SSP.

Conclusion

On the surface, the lack of ability to perform full-scale nuclear testing may pose a concern regarding the United States' capability to certify the reliability of the stockpile. As demonstrated by the current premier capabilities and future plans for the SSP, however, being forced to understand the detailed science of both weapons function and diagnostics allows the observers to answer questions that would otherwise never have been asked during the testing era. The design and calibration of the in-beam monitor system serve as an example to support the level of detail and rigor that goes into understanding weapons design taking the bottom-up approach, which enhances understanding of weapons and therefore the robustness of the stockpile in the absence of testing.

The current approach to stockpile certification vastly differs from the past, which necessitates new tools and capabilities that are currently operational or under development.[20] There will constantly be a need to further the capabilities of the SSP as new questions and challenges emerge, as demonstrated by this work. At the present time, however, giant leaps in scientific capabilities are being taken that will soon find the SSP even more robust than ever. This is not to say that the United States is currently lacking in capabilities, but that it is perpetually driven to enhance capabilities rather than remain satisfied by the status quo. There is currently no technical reason to resume testing, as the SSP works extraordinarily well in ensuring the reliability of the nuclear arsenal. It is possible, however, that, "If a technical problem emerges that cannot be resolved by science-based tools, consideration of a return to nuclear testing may become warranted."[21]

While there is currently no problem that is considered unsolvable by science-based stewardship, it is necessary to remain vigilant and dedicated to continuing to dig deeper into the understanding of weapons systems and the scientific tools used to validate their performance should some unforeseen challenge arise. It is impossible to speculate as to whether future problems unsolvable with science-based stewardship will arise, but it is clear that science-based stewardship and the philosophy of constantly enhancing capabilities with scientific rigor has and will continue to improve understanding of the stockpile compared to the testing era. Turning to science to steward the stockpile has not only resulted in a deeper understanding of weapons function by taking a bottom-up approach to the design and certification process but has allowed the United States to serve as an example to other nations by maintaining compliant nuclear posture on the world stage.

[20] McCoy, "Weapon Certification."
[21] Courtney and Klotz, "Nuclear Testing not Needed."